A DECENTRALIZED MODEL REFERENCE ADAPTIVE CONTROLLER FOR LARGE-SCALE SYSTEMS

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Abstract: A decentralized model reference adaptive controller (MRAC) for a class of large-scale systems with unmatched interconnections is developed in this paper. A new reference model is proposed for the class of large-scale systems considered and a stable decentralized adaptive controller is developed for each subsystem of the large-scale system. It is shown that with the proposed decentralized adaptive controller, the states of the subsystems can asymptotically track the desired reference trajectories. To substantiate the performance of the proposed controller, a large web processing line, which mimics most of the features of an industrial web process line, is considered for experimental study. Extensive experiments were conducted with the proposed decentralized adaptive controller and an often used decentralized industrial PI controller. A representative sample of the comparative experimental results is shown and discussed.

Keywords: Decentralized control, adaptive control, large-scale systems, web winding systems, material processing

1. INTRODUCTION

Large-scale interconnected systems appear in a variety of engineering applications such as power systems, large structures, manufacturing processes, communication systems, transportation systems, and large scale economic systems. Decentralized control schemes present a practical and efficient means for designing control algorithms which utilize only the state of each subsystem without any information from other subsystems. The ease and flexibility of designing controllers for subsystems formed an important motivation for the design of decentralized schemes since information exchange between subsystems is not needed. Consequently, the decentralized adaptive control problem for large-scale systems received and continues to receive considerable attention in the literature in the last two decades (see for example, Sandell et al. (1978); Ioannou (1986); Gavel and Siljak (1989); Ikeda (1989); Siljak (1991); Narendra and Oleng (2002); Mirkin and Gutman (2003)).

In Sandell et al. (1978), a survey of early results in decentralized control of large scale systems was given. Stabilization and tracking using decentralized adaptive controllers was considered in Ioannou (1986) and sufficient conditions were established which guarantee boundedness and exponential convergence errors; this result was pro-

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vided for the case where the relative degree of the transfer function of each decoupled subsystem is less than or equal to two. Decentralized control schemes that can achieve desired robust performance in the presence of uncertain interconnections can be found in Ikeda (1989). A large body of literature in decentralized control of large scale systems can be found in Siljak (1991). Considering systems with matched interconnections, in Narendra and Oleng (2002), it is shown that in strictly decentralized adaptive control systems, it is theoretically possible to asymptotically track the desired outputs with zero error.

In this research, we consider a new reference model for each subsystem that depends on the reference trajectory of the overall large-scale system; that is, there is coupling between individual subsystem reference models. As a result, the proposed design relies on the fact that each subsystem knows the reference trajectory of other subsystems in the design of its decentralized controller. Further, much of the past research has concentrated on the interconnections being matched. In this research, we consider a class of large-scale systems with unmatched interconnections; the web processing application, where the interconnections are unmatched, directly falls into this class.

To validate the control scheme proposed, a large scale system is considered and the control scheme is implemented on it. The system considered for this purpose is a High Speed Web Line (HSWL) at Web Handling Research Center (WHRC), Oklahoma State University (OSU). The HSWL is a large state-of-the-art experimental platform that mimics most of the features of a real-life web process line; details about the platform are given in Section 4.

The contributions of the paper are the following. (1) A new MRAC solution to a class of large-scale systems with unmatched interconnections is proposed. (2) The proposed MRAC solution is implemented on a state-of-the-art web handling experimental setup which mimics most of the features of a real-life web process line.

The remainder of the paper is organized as follows. Section 2 presents the problem statement and the new reference model. The problem of designing a stable MRAC is reduced to that of finding a solution to the Algebraic Riccati Equation (ARE) in Section 3 and a decentralized controller for each subsystem is proposed. The experimental web platform is described in Section 4 and the dynamic model of the experimental platform is also presented. Comparative experimental results with the proposed MRAC design and an industrial PI controller are presented in Section 4.2. Conclusions of the research are given in Section 5.

2. THE PROBLEM STATEMENT

We consider a large-scale system, $\mathbb{S}$, consisting of $(N+1)$ subsystems; each subsystem, $\mathbb{S}_i$, is described by

$$\mathbb{S}_i : \quad \dot{x}_i(t) = A_i x_i(t) + b_i u_i(t) + \sum_{j=0, j\neq i}^{N} A_{ij} x_j(t) \tag{1}$$

where $x_i(t) \in \mathbb{R}^{n_i}$ is the state of the i-th subsystem and $u_i(t) \in \mathbb{R}$ is the input for all $i \in I = \{0, 1, \cdots, N\}$. Notice that the interconnection term (last term) in (1) is unmatched. It is assumed that b_i and A_{ij} are known. Each subsystem matrix, $A_i \in \mathbb{R}^{n_i \times n_i}$ is uncertain but it is assumed that there exist constant vectors $k_i \in \mathbb{R}^{n_i}$ such that, for an asymptotically stable matrix A_{mi},

$$(A_i - A_{mi}) = b_i k_i^\top . \tag{2}$$

The entire large-scale system, $\mathbb{S}$, can be represented by

$$\mathbb{S} : \dot{x}(t) = Ax(t) + Bu(t) \tag{3}$$

where A is a matrix composed of block diagonal matrix elements A_i and off-diagonal matrix elements A_{ij}, and B is a block diagonal matrix composed of b_i, $x^\top(t) = [x_0^\top(t), \ldots, x_N^\top(t)]$, $u^\top(t) = [u_0(t), \ldots, u_N(t)]$, We assume that the pair (A, B) is controllable.

Existing research (see for example, Ioannou (1986); Gavel and Siljak (1989); Narendra and Oleng (2002)) has considered the decentralized MRAC problem for large-scale systems with a reference model given by

$$\dot{x}_{mi}(t) = A_{mi} x_{mi}(t) + b_i r_i(t) \tag{4}$$

where $x_{mi}(t)$ are the reference state vectors and $r_i(t)$ are bounded reference inputs. In this research, we consider a different structure for the reference model by making use of the known interconnection matrices, A_{ij}, in the reference model. The reference model for each individual subsystem, $\mathbb{S}_{mi}$ is described by the equations

$$\begin{aligned} \mathbb{S}_{mi} : \ \dot{x}_{mi}(t) &= A_{mi} x_{mi}(t) + b_i r_i(t) - b_i k_{mi}^\top x_m \\ &+ \sum_{j=0, j\neq i}^{N} A_{ij} x_{mj}(t). \end{aligned} \tag{5}$$

where $k_{mi} \in \mathbb{R}^n$, $n = n_0 + n_1 + \cdots + n_N$, and $x_m^\top(t) = [x_{m0}^\top,\ x_{m1}^\top,\ \cdots,\ x_{mN}^\top]$. With the structure for the reference model (5), the condition for existence of solution to the control problem can be specified in terms of the state matrices of the reference model, A_{mi}, as given by equation (13) later.

The reason for including the term $b_i k_{mi}^\top x_m$ in (5) becomes clear when we consider the reference model for the entire large-scale system which is given by

$$\mathbb{S}_m : \dot{x}_m(t) = A_m x_m(t) + Br(t) - BK_m^\top x_m. \tag{6}$$

where $r^\top(t) = [r_0(t), \ldots, r_N(t)]$, $K_m = [k_{m0}, \ldots, k_{mN}]$, and

$$A_m = \begin{bmatrix} A_{m0} & A_{01} & A_{02} & . & . & . & A_{0N} \\ A_{10} & A_{m1} & A_{12} & . & . & . & A_{1N} \\ . & . & & & & & . \\ A_{N0} & A_{N1} & . & & . & . & . & A_{mN} \end{bmatrix} .$$

Notice that if A_m is not stable for given A_{mi}, then one can place the eigenvalues of $A_m - BK_m^\top$ by choosing K_m. If A_m is asymptotically stable for given A_{mi}, then one can simply choose K_m to be the null matrix.

The goal is to design bounded decentralized control inputs $u_i(t)$ such that $x_i(t)$ are bounded and the error $e_i(t) = x_i(t) - x_{mi}(t)$ converges to zero, that is, $\lim_{t\to\infty} e_i(t) = 0$ for all $i \in I = \{0, 1, \ldots, N\}$. The proposed controller and the stability of the closed-loop system are presented in Section 3 below.

3. CONTROLLER DESIGN AND STABILITY

A few definitions and results useful in the proof are given in Section 3.1 followed by the main result in Section 3.2.

3.1 Preliminaries

Definition 1. Byers (1988) Suppose $A \in \mathbb{C}^{n\times n}$ has no eigenvalue on the imaginary axis. Let $U \subset \mathbb{C}^{n\times n}$ be the set of matrices with at least one eigenvalue on the imaginary axis. The distance from A to U is defined by

$$\delta_s(A) = \min\left\{\|E\| \ : \ A + E \in U\right\}. \tag{7}$$

It can be shown thatByers (1988)

$$\delta_s(A) = \min_{\omega\in\mathbb{R}} \sigma_{\min}(A - j\omega I). \tag{8}$$

Lemma 1. Byers (1988) Let $\rho \geq 0$ and define

$$H_\rho = \begin{bmatrix} A & -\rho I \\ \rho I & -A^\top \end{bmatrix}. \tag{9}$$

Then H_ρ has an eigenvalue whose real part is zero if an only if $\rho \geq \delta_s(A)$. This theorem characterizes $\delta_s(\cdot)$ by

$$\delta_s(A) = inf\ \{\rho \ : \ H_\rho \text{ is hyperbolic}\}. \tag{10}$$

Algorithms to compute $\delta_s(\cdot)$ are illustrated in Byers (1988); He and Watson (1998); Loan (1985).

Lemma 2. Aboky et al. (2002) Consider the Algebraic Ricatti Equation

$$A^\top P + PA + PRP + Q = 0. \tag{11}$$

If $R = R^\top \geq 0$, $Q = Q^\top > 0$, A is Hurwitz, and the associated Hamiltonian matrix $\mathcal{H} = \begin{bmatrix} A & R \\ -Q & -A^\top \end{bmatrix}$ is hyperbolic, i.e., $\mathcal{H}$ has no eigenvalues on the imaginary axis, then there exists a unique $P = P^\top > 0$, which is the solution of the ARE (11).

3.2 Main Result

Theorem 3. Given the large scale system (1) and the reference model (5), there exists a positive definite matrix $P_i = P_i^\top$ such that the decentralized control law and the parameter updation law given by

$$u_i(t) = r_i(t) - k_{mi}^\top x_m(t) - \hat{k}_i^\top x_i(t) \tag{12a}$$

$$\dot{\hat{k}}_i(t) = -(e_i^\top(t) P_i b_i) x_i(t) \tag{12b}$$

where $\hat{k}_i$ is estimate of k_i, render the closed-loop system exponentially stable if

$$\delta_s(A_{mi}) > \sqrt{N\xi_i}. \tag{13}$$

Proof: Define subsystem errors as $e_i(t) \triangleq x_i(t) - x_{mi}(t)$. Then, the error dynamics of the closed-loop system defined by (1), (5), and (12) can be obtained as

$$\dot{e}_i(t) = A_{mi} e_i(t) + b_i \tilde{k}_i^\top(t) x_i(t) + \sum_{j=0, j\neq i}^{N} A_{ij} e_j(t). \tag{14}$$

where $\tilde{k} \triangleq k_i - \hat{k}$. Consider the following Lyapunov function candidate

$$V(e_i, \tilde{k}_i) = \sum_{i=0}^{N} (e_i^\top P_i e_i + \tilde{k}_i^\top \tilde{k}_i). \tag{15}$$

The derivative of the Lyapunov function candidate along the trajectories of (14) and (12b) is given by

$$\begin{aligned} \dot{V}(e_i, \tilde{k}_i) = \sum_{i=0}^{N} (& e_i^\top (A_{mi}^\top P_i + P_i A_{mi}) e_i \\ & + \sum_{j=0, j\neq i}^{N} [\underbrace{e_i^\top P_i}_{\alpha^\top} \underbrace{A_{ij} e_j}_{\beta} + \underbrace{e_j^\top A_{ij}^\top}_{\beta^\top} \underbrace{P_i e_i}_{\alpha}]). \end{aligned} \tag{16}$$

Using the inequality $\alpha^\top\beta + \beta^\top\alpha \leq \alpha^\top\alpha + \beta^\top\beta$, $\forall \alpha,\ \beta \in \mathbb{R}^{n_i}$, for terms in braces in (16) and rearranging the terms, we obtain

$$\begin{aligned} \dot{V}(e_i, \tilde{k}_i) \leq & \sum_{i=0}^{N} \{ e_i^\top (A_{mi}^\top P_i + P_i A_{mi}) e_i + N e_i^\top P_i^2 e_i. \\ & + e_i^\top \underbrace{\left(\sum_{j=0, j\neq i}^{N} A_{ij}^\top A_{ij} \right)}_{X_i} e_i \} \\ \leq & \sum_{i=0}^{N} \left\{ e_i^\top (A_{mi}^\top P_i + P_i A_{mi} + N P_i^2 + \xi_i I) e_i \right\} \end{aligned} \tag{17}$$

where $\xi_i \triangleq \lambda_{max}(X_i)$. Therefore, if there exist symmetric positive definite matrices P_i such that

$$A_{mi}^\top P_i + P_i A_{mi} + P_i (NI) P_i + (\xi_i + \epsilon_i) I = 0 \tag{18}$$

for $\epsilon_i > 0$ then

$$\dot{V}(e_i, \tilde{k}_i) \leq -\sum_{i=0}^{N} \epsilon_i e_i^\top e_i\ . \tag{19}$$

and $V(e_i, \tilde{k}_i)$ qualifies as a Lyapunov function and the equilibrium point $e_i = 0$ is exponentially stable for all $i \in I$. Proof of Theorem 3 now rests on the existence of symmetric positive definite solution P_i to the ARE (18). To this end, we invoke Lemma 2. Define the Hamiltonian for the ARE (18) as

$$\mathcal{H}_i = \begin{bmatrix} A_{mi} & NI \\ -(\xi_i + \epsilon_i)I & -A_{mi}^\top \end{bmatrix}. \tag{20}$$

The eigenvalues of the Hamiltonian may be found by writing

$$\begin{aligned} det(sI - \mathcal{H}_i) &= \begin{bmatrix} sI - A_{mi} & -NI \\ (\xi_i + \epsilon_i)I & sI + A_{mi}^\top \end{bmatrix} \\ &= det[G(s)] = 0. \end{aligned} \tag{21}$$

where $G(s) = [(sI + A_{mi})^\top (sI - A_{mi}) + N(\xi_i + \epsilon_i)I]$. From (21), it may be seen that $\mathcal{H}_i$ is hyperbolic if $G(j\omega)$ is non singular. Notice that,

$$\begin{aligned} -G(j\omega) &= -(j\omega I + A_{mi})^\top (j\omega I - A_{mi}) - N(\xi_i + \epsilon_i)I \\ &= \underbrace{(A_{mi} - j\omega I)^H (A_{mi} - j\omega I)} - N(\xi_i + \epsilon_i)I. \end{aligned} \tag{22}$$

From (8), we see that the term in braces in (22) is always greater than $\delta_s^2(A_{mi})I$. Thus, if

$$\delta_s^2(A_{mi}) - N\xi_i > 0 \tag{23}$$

we can always choose a value for ϵ as $\gamma(\delta_s^2(A_{mi}) - N\xi_i)/N$ for some γ in the range $0 < \gamma < 1$ to make $-G(j\omega)$ in (22) positive definite, thus ensuring the existence of a symmetric positive definite P_i to satisfy the ARE (18). $\diamondsuit$

Section 4 briefly presents details about the experimental platform considered for implementation of the proposed control algorithm, the dynamic model of the plant, and the experimental results.

4. WEB PROCESSING APPLICATION

A web is any material which is manufactured and processed in continuous, flexible strip form. Examples include paper, plastics, textiles, strip metals, and composites. Web processing pervades almost every industry today. It allows us to mass produce a rich variety of products from a continuous strip material. Products that include web processing somewhere in their manufacturing include aircraft, appliances, automobiles, bags, books, diapers, boxes, newspapers, magnetic tapes, and many more. Typically, web process lines consist of an unwind section, one or more process sections, and a rewind section. Web tension and velocity in each of these sections are key variables that influence the quality of the finished web and hence the products manufactured from it.

Figure 1 shows a picture of the experimental platform. It is possible, theoretically, to "decentralize" this large scale system into subsystems in an arbitrary way. However, it is convenient if subsystems are chosen as physically identifiable segments in the system. Consequently, four "sections" are identified as subsystems in Figure 1: (1) unwind section, (ii) master speed section, (ii) process section, and (iv) rewind section. Each of these sections is equipped with a drive motor to impart velocity/tension to the web and sensors (loadcells for tension measurement and encoder or some other sensor for speed measurement). As the name indicates, the master speed section has a driven roller which is used to set the reference web transport speed for the entire web line, and is generally the first driven roller upstream of the unwind roll in almost all web process lines. This section is not used to regulate the tension in the spans adjacent to it. Except the master speed section, all the other sections use two local feedback signals, namely, the web tension and web velocity; the master speed section uses only the web velocity as feedback signal. Figure 2 shows

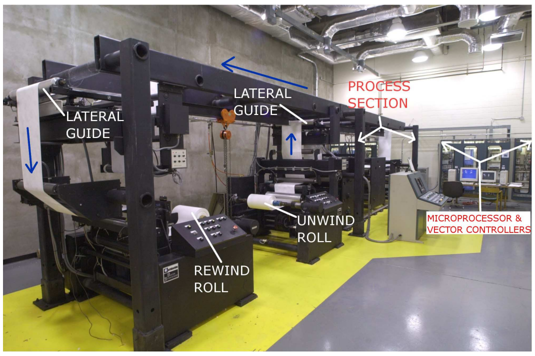

Fig. 1. Picture of the Experimental Web Platform

a line sketch of the decentralization scheme considered. In Figure 2, M_0, M_2 and M_3 are the drive motors for the unwind section, process section, and the rewind section and M_1 is the drive motor for master speed section. Except for M_1, the other motors use a tension feedback (from loadcell, indicated by LC in Figure 2) and a speed feedback. The motors M_0 and M_3 in Figure 2

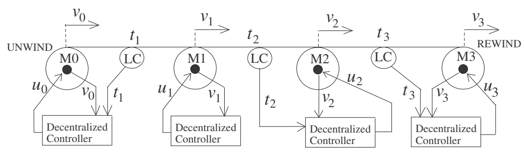

Fig. 2. Sketch of the Platform Showing Driven Rolls/Rollers and Tension Zones

are 30 bhp (brake horse power), 3-phase RPM AC motors under vector control where as the motors M_1 and M_2 are 15 bhp, 3-phase RPM AC motors under analog HR-2000 control. The motor drive systems, the real-time architecture which includes micro-processors, I/O cards, and the real time control environment AutoMax, and the other mechanical hardware are from Rockwell Automation. The lateral guides shown in Figure 1 are Fife displacement guides. These guides are controlled independent from the real-time control software through dedicated controllers.

The dynamics of each of the four sections is briefly presented in the following.

4.1 Dynamic Model

Nonlinear dynamic models for each of the sections in web processing line are developed in Brandenbuerg (1972); Whitworth and Harrison (1983). For the purpose of implementation, these nonlinear models are linearized around an equilibrium point. Such linearized models may be found in Shelton (1986); Siraskar (2004).

Unwind Section:

$$\dot{x}_0 = \begin{bmatrix} \dot{T}_1 \\ \dot{V}_0 \end{bmatrix} = A_0 x_0 - b_0 U_0 + \sum_{j=1}^{3} A_{0j} x_j \qquad (24)$$

where A_{02} and A_{03} are null matrices, and

$$A_0 = \begin{bmatrix} \frac{-v_{r1}}{L_1} & \frac{(t_0 - AE)}{L_1} \\ \frac{R_0^2/J_0}{} & \frac{-b_{f0}}{J_0} \end{bmatrix}, \; b_0 = \begin{bmatrix} 0 \\ \frac{n_0 R_0}{J_0} \end{bmatrix}, \; A_{01} = \begin{bmatrix} \frac{AE - t_{r1}}{L_1} \\ 0 \end{bmatrix}$$

Master Speed Section:

$$\dot{x}_1 = \dot{V}_1 = A_1 x_1 + b_1 U_1 + \sum_{j=0, j\neq 1}^{3} A_{1j} x_j \qquad (25)$$

where $A_1 = -b_{f1}/J_1, \; b_1 = n_1 R_1/J_1, \; A_{10} = \left[\frac{-R_1^2}{J_1}, 0\right]$, $A_{12} = \left[\frac{R_1^2}{J_1}, 0\right], \; A_{13} = [0, 0]$

Process Section and Rewind Section:

$$\dot{x}_i = \begin{bmatrix} \dot{T}_i \\ \dot{V}_i \end{bmatrix} = A_i x_i + b_i U_i + \sum_{j=0, j\neq i}^{3} A_{ij} x_j \qquad (26)$$

for $i = 2, 3$ where $A_i = \begin{bmatrix} \frac{-v_{ri}}{L_2} & \frac{(AE - t_{ri})}{L_i} \\ \frac{-R_i^2}{J_i} & \frac{-b_{fi}}{J_i} \end{bmatrix}$, $b_i = \begin{bmatrix} 0 \\ \frac{n_2 R_2}{J_2} \end{bmatrix}$, $A_{20} = \begin{bmatrix} \frac{v_{r1}}{L_2} & 0 \\ 0 & 0 \end{bmatrix}$, $A_{21} = \begin{bmatrix} \frac{t_{r1} - AE}{L_2} \\ 0 \end{bmatrix}$, $A_{23} = \begin{bmatrix} 0 & 0 \\ \frac{R_2^2}{J_2} & 0 \end{bmatrix}$ $A_{32} = \begin{bmatrix} \frac{v_{r2}}{L_3} & \frac{t_{r2} - AE}{L_3} \\ 0 & 0 \end{bmatrix}$ Notice that the elements of the interconnection matrices A_{ij}, and the elements of the input matrices b_i involve the roller radii, the polar moments of inertia, the reference tension/velocity, gearing ratio between the drive motor and the driven roller, and the web material properties. These quantities are known in advance. However, the system matrices A_i contain a term with coefficient of viscous friction which is unknown.

4.2 Experiments

To evaluate the effectiveness of the proposed controller, two sets of experiments were conducted. In the first set of experiments, a control scheme using Proportional-Integral (PI) controllers, which is currently used in most of the industrial web process lines, is implemented. This control scheme incorporates a tension control loop and a velocity control loop for each section (except for the master speed section which uses only a speed control loop). Though this scheme is very simple to implement, its performance is often limited and tuning the P and I gains is a tedious process. In the second set of experiments, the proposed controller is implemented. Experimental results with these control schemes show that the proposed control scheme offers a marked improvement in terms of lesser web tension error. The results of experiments with PI control scheme are presented in Section 4.2.1 and the results of experiments with the proposed controller are presented in Section 4.2.2.

4.2.1. Results with PI Control Scheme A series of experiments were conducted using the PI control scheme at different reference web tensions and different reference web velocities. In each case, the PI controllers were tuned carefully to yield best possible performance. As a representative sample, results of experiments conducted with PI control scheme at 1000 fpm are presented. The reference web tension was set to 14.35 lbf. Figure 3 shows the web velocity error at master speed section and the web tension error at each section. The top plot in Figure 3 shows the velocity error at master speed section. The subsequent plots in the figure show the tension error at each section. It can be seen from Figure 3 that there is considerable deviation of web tension from reference tension. Such variations in web tension are undesirable since they deteriorate the quality of the product made from web.

4.2.2. Results with the Proposed Controller In the second set of experiments, the proposed controller is implemented with the same reference web velocities and reference web tensions under the same conditions. Numerical values of various parameters used in the control design are: v_{ri}=1000 fpm, t_{ri} =14.35 lbf, L_1= 20 ft, L_2=33 ft, L_3=67 ft, J_0=8 lbf-ft^2, $J_1 = J_2$=2 lbf-ft^2,J_3=4 lbf-ft^2, AE=2000 lbf, $n_0 = n_3 = 0.5$, $n_1 = n_2 = 1$, R_0=1.25 ft, $R_1 = R_2$=0.339 ft, R_3=0.67 ft.

The matrices A_{mi} are chosen as explained in the following. For the unwind section, $A_{m0} = [-v_{r0}/L_1, \; (AE - t_0)/L_1 \; ; \; C_{01}, \; -C_{02}]$ where $C_{01} = 120$ and $C_{02} = 2000$; for the master speed section, $A_{m1} = C_{12} = 4000$; for the process and rewind sections, $A_{mi} = [-v_{ri}/L_i, \; (AE - t_{ri})/L_i \; ; \; -C_{i1} \; , \; -C_{i2}]$ for $i = 2, 3$ where $C_{21} = 1500$, $C_{22} = 400$, $C_{31} = 15$, $C_{32} = 15$.

It is verified that the condition given in (23) is satisfied for the given matrices A_{mi}. The LQR algorithm is used to obtain the feedback gain K_m, which ensures that the reference states go to their desired values in an optimal sense and the rows of K_m are k_{m0}, k_{m1}, k_{m2}, and k_{m3} respectively. The values of C_{ij} and K_m given above are computed for reference web velocities of 1000 fpm and 1500 fpm and a reference web tension of 14.35 lbf and controller given in (12) is implemented.

Figure 4 shows experimental results conducted at a reference web velocity of 1000 fpm. The top plot in Figure 4 shows the web velocity error at master speed section and the subsequent plots show web tension errors at each section. It can be observed that there is a substantial reduction in the amplitude of tension errors – to the tune of 75% – at each section as compared to the industrial PI control scheme.

5. CONCLUSIONS

Decentralized adaptive controller design for a class of large-scale systems with unmatched interconnections is investigated. A new reference model that includes known interconnections is considered and a stable decentralized MRAC design is proposed. A large experimental web line is used for evaluating the proposed decentralized design. Comparative experimental results with an often used industrial PI controller show that the proposed decentralized design gives improved regulation of web tension.

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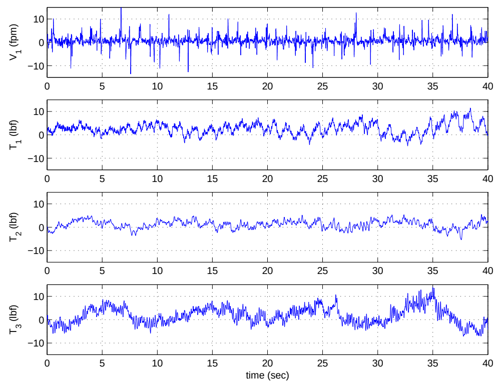

Fig. 3. Decentralized PI controller: Reference velocity 1000 ft/min

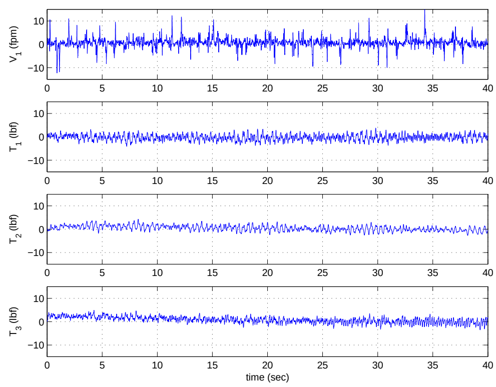

Fig. 4. Decentralized adaptive controller: Reference velocity 1000 ft/min